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CHANGES IN THE MAGNITUDE AND TRANSFORMATION OF FLOOD WAVES SUBSEQUENT TO THE CHANNELIZATION OF THE RABA RIVER, POLISH CARPATHIANS

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ABSTRACT

Alterations in flood flows of the Raba River are examined to determine the influence exerted on flood waves by changing morphological conditions. With stable vertical channel position, the river increased its sinuosity during the 1920s to 1940s, and the change was accompanied by a growing tendency to flood-wave attenuation. The temporal change in flood-wave transformation is typical of a developing low-flow system. Subsequently, streambed degradation has been induced due to channnelization works which straightened and narrowed the river. Flood waves became progressively more flashy as channel incision progressed. The increase in magnitude of flood waves passing the deepened reach was greatest for bankfull flows and diminished for lower in-bank flows and higher overbank flows.

The tendency to magnification of peak discharges has been also found in other Carpathian rivers which were considerably degraded in the 20th century in response to channelization. Introducing an empirically found correcting factor into the analysis of the ratio of outflow to inflow peak discharges shows how the conditions of peak-flow transformation in a reach have changed since the beginning of the study period. A marked coincidence between changes in vertical channel location and variations in the 'corrected' peak-discharge ratio proves channel changes to be a very important reason for the growing flood hazard in southern Poland.

Gradient oversteepening and channel narrowing, caused by channelization, lead to formation of a river system having a steep, straight, narrow and deep channel. Such a morphology distinguishes the system from natural low-flow and high-flow systems. Reduced floodplain water storage and self-acceleration of flow concentrated in a channel zone make flood waves progressively more flashy on their way down the channelization-formed system.

KEY WORDS channelization; channel incision; flood magnitude; flood-wave transformation; channelization system

INTRODUCTION

Channelization works have been carried on in the middle and lower courses of Carpathian tributaries to the Vistula River since the beginning of the present century (Kędzior, 1928) to minimize flood hazard and stabilize channel position within the valley floors. The works, especially intensive in the last 30 years, have resulted in straightening and a considerable shortening of the rivers as well as in narrowing of their channels (Klimek, 1987; Wyżga, 1991). The ensuing increase in flow velocity and stream power has brought the rivers into a disequilibrium, and streambed degradation has been initiated as a compensating mechanism (Wyżga, 1993b). Channels incision of 1·5–3·3 m had occurred by 1980 (Wyżga, 1991), and the downcutting is still continuing in many sections of the main Carpathian rivers.

The stream-channel and floodplain system developed for a dominant flow is known to have a persistent effect on flood waves moving down a river (Burkham, 1976). A low-flow system, developed by and for low flood flows and characterized by a low-gradient, sinuous, narrow, deep channel, attenuates flood waves passing through the reach. On the other hand, the shape of flood waves passing the steep, relatively straight, wide and

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shallow channel of a high-flow system is not altered, and their peak discharges are sustained. However, little attention has been given so far to the influence exerted upon flood waves by an 'unnatural', channelization-formed system being characterized by a steep, straight, narrow and deep channel.

This paper describes changes in flood flows passing the Raba, a mountain gravel-bed river of the temperate zone, subsequent to regulation of its channel. The results of the case study are next confronted with data from other Carpathian rivers. The purpose of the paper is to show and explain the modifying effect of channel regulation upon flood flows, and to discuss implications of the transformation of flood flows for river engineering and environmental planning.

FIELD SETTING AND CHANNEL REGULATION HISTORY

The Raba River drains the northern slopes of the Western Carpathians. The low retention potential of the flysch bedrock, high relief and the low forest cover of the basin result in great variability of water stage and discharge of the river (Punzet, 1969). Detailed information on physiography of the Raba River drainage basin and hydrology of the river, as well as on location of the study reach, are presented elsewhere (Wyżga, 1991).

Data from two gauging stations – the Gdów station situated in the middle course of the river and the Proszówki station in its lower course – have been used for the analysis of temporal changes in spatial transformation of flood waves. The record of maximum annual discharges since 1921 and of daily discharges since 1951 for the stations is available from the Hydrologic Survey. The length of the Gdów–Proszówki reach is 26·75 km, and channel slope changes from 0·00117 near Gdów to 0·00068 near Proszówki. Mean annual discharge (1951–1980) amounts to 12·1 $m^3 s^{-1}$ for the upper station (G) and 17·6 $m^3 s^{-1}$ for the lower one (P).

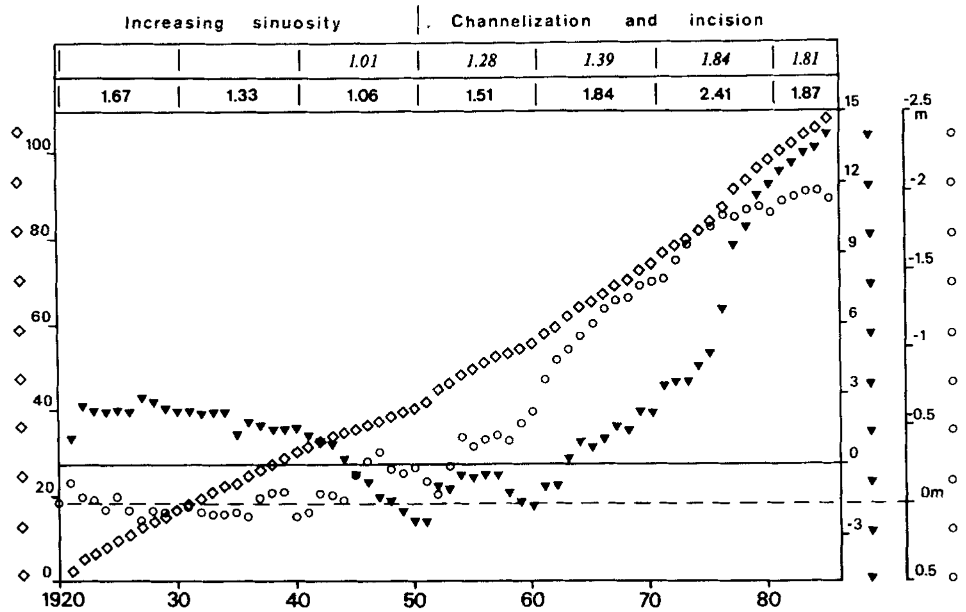

Figure 1. Flood-flow changes in the middle and lower Raba River channel between 1921 and 1985 as shown by annual maxima. (◇) Cumulative values of the ratio of maximum annual discharge at the downstream (Proszówki) and upstream (Gdów) gauging stations; at the top of the figure are shown decade averages of the ratio of peak flows at both stations computed for annual maxima (Roman) and the 10 largest floods of a decade (italic); (▼) cumulative values of the 'corrected' ratio of the maximum annual discharges; (O) changes in vertical channel location in the Gdów–Proszówki reach since 1920. The data are weighted means, alterations in the extreme stations (Gdów and Proszówki) accounting for one-quarter of the total change each, and those in the middle of the reach (Książnice station) for one-half

At the end of the 19th century the Raba was a relatively shallow and wide aggrading river. It formed a typical high-flow channel system of a bed-load stream (Wyżga, 1993a). The first phase of channelization during the first decades of the present century caused a 12 per cent shortening of the river in the Gdów–Proszówki reach, and some narrowing of the channel. It induced channel downcutting in the reach by *c.* 0·5 m during the 1910s which was followed by vertical channel stability in the 1920s to 1940s (Figure 1).

Alterations in basin management caused progressive reduction in sediment supply from the basin during the first half of the present century (Wyżga, 1993a). As a result, by about 1950 the tendency to meandering reappeared in the single-thread channel formed by the regulation. The cessation of river-control works during and immediately after the Second World War allowed the river to increase considerably its sinuosity upstream of Gdów. Since most regulation structures in the Gdów–Proszówki reach survived, its length did not change significantly; however, thalweg length must have increased with the onset of active meandering.

The channelization works were resumed late in the 1950s. Further shortening of the river by 7 per cent took place in the reach, and the channel was considerably narrowed. Aerial photos of the 17 km long reach upstream and downstream of Gdów show that between 1955 and 1987 the low-flow channel width diminished by about 40 per cent, but the decrease in width of the bed-material transport zone was much greater and amounted to about 60 per cent (Table I). Rapid streambed degradation has been induced by this second phase of channelization; in the Gdów–Proszówki reach channel incision of 2 m has occurred since the 1950s (Figure 1).

Summarizing, the first phase of the 20th century channelization did not change markedly the balance between sediment supply and transporting ability of the river, and the Raba retained the character of a high-flow system. Subsequently, the river started to evolve into a low-flow system due to the reduction in sediment yield of the basin. Streambed degradation has been an important river response to the repeated channelization (Wyżga, 1993b), and an 'unnatural' (maintained by regulation structures) channel – steep, straight, narrow and deep – has originated.

TRANSFORMATIONS OF FLOOD WAVES IN THE RABA CHANNEL

Annual maxima analysis

Several methods may be used to examine the way in which channel changes affected flood waves in their downstream movement. One of them employs annual maxima for the inflow (Gdów) and outflow (Proszówki) gauging stations, and shows temporal changes in the ratio of annual peak discharge recorded in the downstream and upstream station (Figure 1). First, there occurred a slow but significant fall in the ratio from 1·67 in the 1920s to 1·06 during the 1940s, followed by a rapid increase to 2·41 in the 1970s. Finally, some reduction of the ratio to 1·87 took place during 1981–1985, whereupon the river impoundment at Dobczyce must have changed the hitherto existing relation between peak flows of the main stream and of its tributaries in the middle and lower course of the Raba River.

Table I. Changes in width of the Raba River channel between Dobczyce and Wieniec in the period 1955–1987 (LFC, low flow channel; FC, flood channel)

	1955		1974		1987	
	LFC	FC	LFC	FC	LFC	FC
Mean width (m)	46·4	137·3	38·9	103·6	29·0	53·7
Standard deviation of width	19·9	63·0	15·2	54·0	11·6	17·1
Smallest width (m)	15	38	12	37	10	27
Greatest width (m)	153	346	96	326	67	118

The pattern of changes is more apparent when the value of 1·45 is subtracted from each annual ratio value. This value represents a multi-year (1951–1985) average of mean annual discharge at both stations and is very close to the average increase of flood-wave volume in the reach for the dozen or so largest floods of the present century (Punzet and Czulak, 1988). On this basis it has been recognized as describing approximately the contribution of the flood-wave volume increase, due to an addition in the lower part of the basin, to the downstream peak-discharge changes. Therefore, negative or positive values of the 'corrected' ratio represent lower and higher downstream growth in peak discharges than could be accounted for by a downstream increase in flood-wave volume, with falls and rises of the cumulative 'corrected'-ratio curve reflecting changing trends of the phenomenon.

When the trends in discharge change are compared with the curve showing alterations in vertical Raba channel location in the Gdów–Proszówki reach since 1920 (Figure 1), a striking coincidence is evident between the rapid channel downcutting commencing at the end of the 1950s and the peak-discharge changes. Since the growth in peak discharges with downstream flood-wave movement was much greater than that accounted for by the addition of water with increasing basin area, a change in shape of flood waves must have occurred, the increasingly peaked nature of flood waves being compensated by their shortened time-bases. On the other hand, the trend towards attenuation of peak discharges in the period of relatively

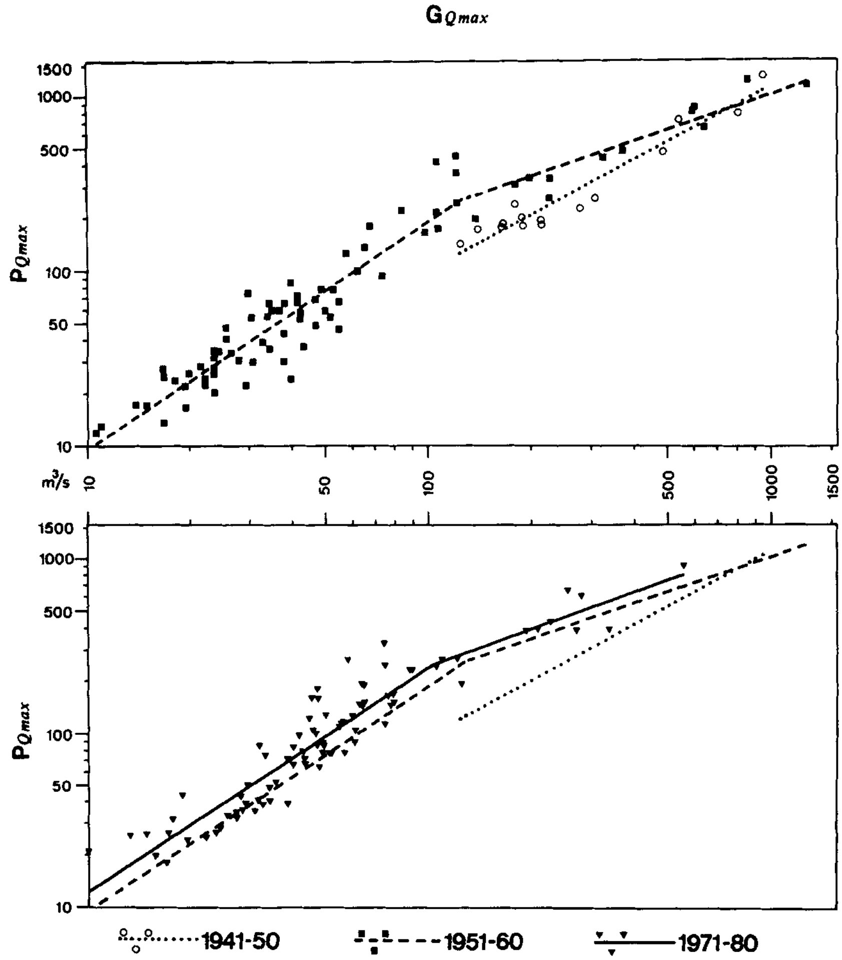

Figure 2. Temporal changes in the relation between the inflow and outflow peak discharges in the Gdów–Proszówki reach as shown by data for the whole range of flood flows occurring in the particular decades and by decade-average regression lines

stable vertical channel position, especially pronounced during the 1940s, may be related to the progressive transformation of the Raba channel into a low-flow system (cf. Burkham, 1976).

A very similar trend has been found when analysing the Proszówki/Gdów peak flow ratio for the ten largest floods of a decade (Figure 1). During the 1940s to 1970s there was a significant increase in the ratio, from 1·01 at the beginning to 1·84 at the end of the period, followed by a small reduction to 1·81 in 1981–1985.

Analysis of decade-average trend lines

An investigation of temporal changes in the relationship between inflow and outflow peak discharges for a broad range of flood flows has been the next step of the analysis. The outflow (P) peak discharges have been determined for each flood peak exceeding 20 $m^3 s^{-1}$ (*c.* twice the mean annual discharge) at the upstream (G) station from discharge records since 1951, and such a procedure has also been applied to the dozen or so largest flows of the 1940s. The data, grouped separately for every decade, have then been plotted on the diagrams of the inflow versus outflow peak discharge (Figure 2) and the inflow peaks versus the outflow/inflow peak ratio (Figure 3), and used to compute decade-average regression lines.

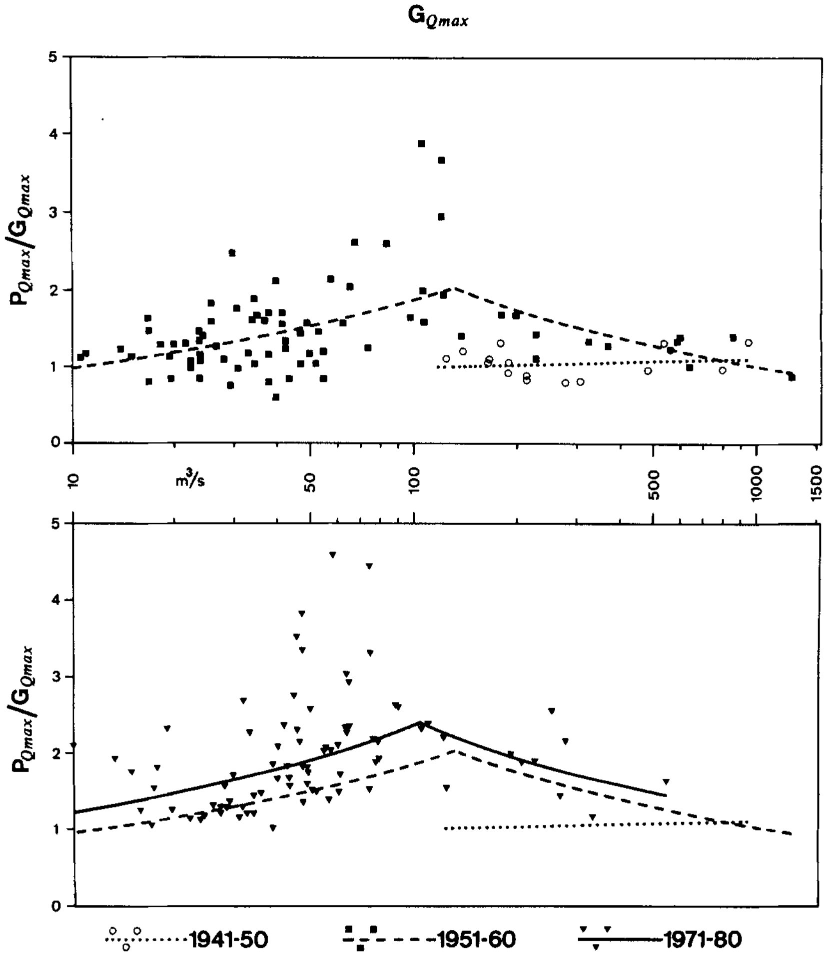

Figure 3. Temporal changes in the relation between the inflow peaks and the degree of magnification of peak discharges in the Gdów–Proszówki reach as shown by data for the whole range of flood flows occurring in the particular decades and by decade-average regression lines

Table II. Temporal changes in the outflow peak discharge (P_{Qmax}) for given inflow peak-discharge values (G_{Qmax}), and in the ratio of peak-flow magnification in the Gdów–Proszówki reach of the Raba River as indicated by the decade-average trend lines shown in Figure 2. The italic typeface is used to distinguish in-bank and overbank flows at the Proszówki station

	P_{Qmax} (m^3 s^{-1})			$P_{Qmax} : G_{Qmax}$		
G_{Qmax} (m^3 s^{-1})	1941–50	1951–60	1971–80	1941–50	1951–60	1971–80
10		*9·6*	*12·2*		0·96	1·22
25		*31·4*	*39·7*		1·26	1·59
50		*76·6*	*97·1*		1·53	1·94
100		*186*	*236*		1·86	2·36
125	*125*	*250*	283	1·00	2·00	2·26
150	*151*	289	322	1·01	1·93	2·15
325	339	482	554	1·04	1·48	1·70
500	532	641	748	1·06	1·28	1·50
1000	1100	1014	1216	1·10	1·01	1·22

Two main conclusions can be drawn from a comparison of the trend lines on Figures 2 and 3 (see also Table II). A distinct change in the transformation of flood waves moving down the reach took place when a certain discharge had been exceeded, which can be reasonably related to the change from in-bank to overbank flow conditions. It allows estimation of a bankfull discharge at the Gdów and Proszówki stations as well as its changes over time. In the 1950s the bankfull discharge amounted to 129 m^3 s^{-1} at Gdów and 259 m^3 s^{-1} at Proszówki, while during the 1970s the respective values were 105 and 252 m^3 s^{-1}. The temporal changes in bankfull discharge correspond well with the fact that mean annual flood at Gdów diminished considerably (from 424 to 208 m^3 s^{-1}), due to climatic fluctuations, between the 1950s and 1970s, but the reduction recorded at Proszówki was relatively little (from 538 to 420 m^3 s^{-1}).

Secondly, marked changes in spatial transformation of flood waves took place between the 1940s and 1970s. During the 1940s the tendency to flood-wave attenuation was highly pronounced in the Raba channel. As a result, peak discharges at Proszówki were, on average, nearly equal to those at Gdów, the degree of magnification of peak discharges in the reach changing from 1·01 for the lowest overbank flows at Gdów to 1·10 for the assumed 1000 m^3 s^{-1} discharge (flow of 23 years recurrence interval) (Table II). Therefore, relatively low overbank flows entering the reach must have been transformed into in-bank flows at its end.

During the 1950s, in-bank flows entering the reach were increasingly magnified with growing inflow peak discharge, the peak-discharge magnification index rising from 0·96 for 10 m^3 s^{-1} at Gdów to 2·00 for bankfull discharge. Then, with further growth in inflow peak discharge, the magnification index fell to 1·01 for the assumed 1000 m^3 s^{-1} discharge. For the best part of the range of overbank flows at Gdów, the outflow peak values were now much higher than in the 1940s. If an average 45 per cent increase in flood-wave volume with growing basin area is taken into account, it appears that waves with inflow peaks in the range 40–325 m^3 s^{-1} must have increased their sharpness passing the Gdów-Proszówki reach, whereas low in-bank flows and flows greater than the mean annual flood were then attenuated there (Table II).

The tendency to increasing peak discharges of flood waves passing the reach was still more intensified during the 1970s. The bankfull discharge at Gdów was now magnified 2·40 times in the reach, and the degree of peak-flow magnification diminished with both lowering in-bank flows and increasing overbank flows, attaining 1·22 at the 10 or 1000 m^3 s^{-1} inflow peak discharge. The range of flood waves being sharpened in the reach expanded considerably; only the waves with inflow peak discharge lower than 20 m^3 s^{-1} or higher than 600 m^3 s^{-1} (i.e. the flows with 6 year or longer recurrence interval) were now flattened there.

The fall in the degree of magnification of overbank flows as an inflow peak discharge increases explains the discrepancy between the decade averages of the ratio computed for either the annual maxima or the 10 largest floods of a decade (Figure 3); the highest discharges of some years originate from near-bankfull flows, and thus result in very high values of the ratio.

Table III. Selected parameters of the inflow (G) and outflow (P) hydrographs for flood waves with the inflow peak discharge of 540–610 $m^3 s^{-1}$ from the 1940s to 1970s

	G_{Qmax} ($m^3 s^{-1}$)	P_{Qmax} ($m^3 s^{-1}$)	P_{hmax} (m asl)	$\frac{P_{Qmax}}{G_{Qmax}}$	$\frac{P_t}{G_t}$	$\frac{P_{t\,50\%}}{G_{t\,50\%}}$	G_{Vex} (%)	P_{Vex} (%)
July 1949	568	696	194·60	1·22	1·23	1·18	74	64
Aug 1955	600	805	195·04	1·34	1·19	1·08	69	65
July 1960	610	850	195·22	1·39	1·17	1·30	66	70
July 1962	580	880	195·34	1·52	1·09	1·09	54	62
June 1965	540	656	194·40	1·21	1·01	1·16	26	34
Aug 1972	584	915	195·48	1·57	1·14	0·91	71	77

G_{Qmax}, P_{Qmax} = peak discharge at Gdów and Proszówki; P_{hmax} = peak stage of a flood at the lower station; P_t, G_t = flood-flow duration at the analysed gauging stations; $P_{t\,50\%}$, $G_{t\,50\%}$ = duration of transfer of the peak half of a flood-wave volume in the gauge cross-sections; G_{Vex}, P_{Vex} = percentage of the flood-wave volume for the discharge exceeding the flow of 50% probability at the gauging stations

Analysis of flood hydrographs

The temporal change in spatial transformation of flood waves was perhaps most pronounced for waves with near-bankfull discharges, as suggested by the highest change in peak-discharge magnification index over the period for such flows; however, insufficient frequency of stage observations during lower floods reduces accuracy of hydrograph reconstruction. Therefore, the set of six waves with inflow peak discharge of 540–610 $m^3 s^{-1}$ from the 1940s to 1970s has been selected for the analysis of temporal changes in the mode of flood-wave transformation (Table III, Figure 4).

When flood waves with similar inflow peaks (see floods of July 1949, July 1962 and August 1972) are compared, the rise in both peak stage and discharge at the lower station is visible, resulting in progressive increase in the degree of downstream peak-flow magnification. This rise in peak stages of subsequent floods at the lower station, along with a significant streambed degradation there, is very significant as it proves the rise in peak discharges to be a real phenomenon, not simply an artifact of wrongly constructed rating curves.

The increasingly peaked nature of flood waves at the lower station was accompanied by a tendency through time to shorten their time-bases. An average ratio of flood duration at Proszówki and at Gdów is lower by about 12 per cent for the last three floods in comparison with the first three. A reduction in the time needed for the peak half of a flood-wave volume to pass the lower station was even somewhat greater over the period, reflecting a combined effect of the shortening of flood duration and changes in concentration of run-off in the peak and limbs of a flood wave. During the first three floods under consideration, transfer of the peak half of flood run-off at Proszówki lasted, on average, 19 per cent longer than at Gdów, but during the last three floods it was only 5 per cent longer at the lower station.

This progressive increase in concentration of flood waves passing the Gdów–Proszówki reach is easily visible if the percentage of the volume of each wave is compared for the discharge exceeding the flow of 50 per cent probability at both stations (240 $m^3 s^{-1}$ at G; 350 $m^3 s^{-1}$ at P). Owing to a specific hydrograph shape of each flood, reflecting the rainfall pattern, only differences between the values at both stations for the same flood are meaningful, not those between floods. The amount of run-off occurring at the time of exceedance of the specified discharge values constituted smaller parts of the flood-wave volume at Proszowki than at Gdów during the floods of 1949 and 1955, but greater during the subsequent floods.

Summarizing, initially mechanisms of flood-wave transformation operating in the reach tended to reduce downvalley the amount of run-off conveyed at a flood peak. Next they were turned to shorten the duration of a flood wave, and to increase considerably its peak discharge.

CHANGES IN PEAK-DISCHARGE RELATION IN OTHER CARPATHIAN TRIBUTARIES TO THE VISTULA

The research reported in the previous section indicates that the channelization-induced river incision leads to the increasingly peaked nature of flood waves moving down a deepened channel; however, such a conclusion

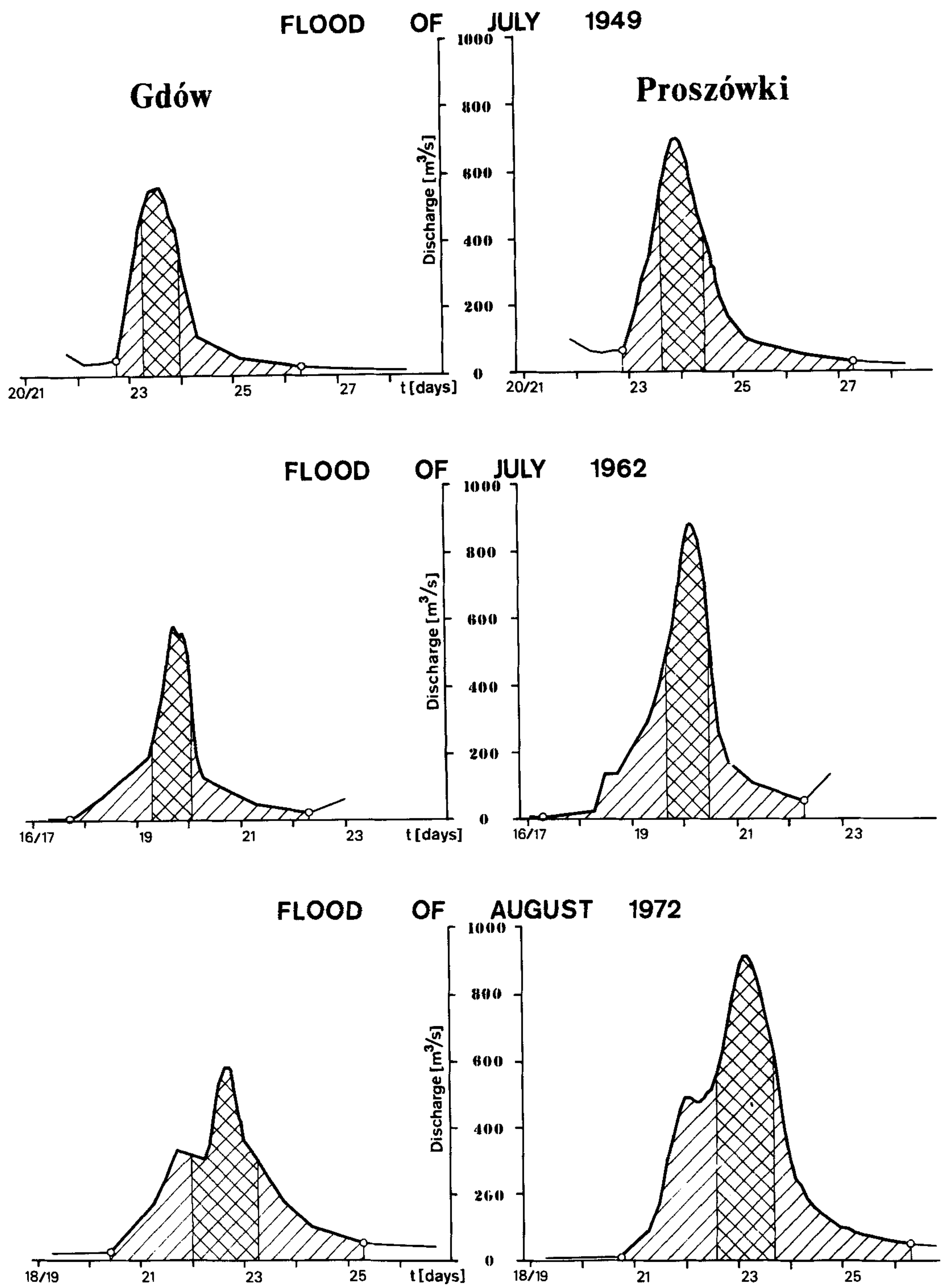

Figure 4. Flood hydrographs at the Gdów and Proszówki gauging stations for the three flood waves with similar inflow peak discharge. Flood run-off is represented by obliquely hatched areas, and the peak half of the flood volume by cross-hatching

needs to be verified for other rivers. Therefore, other Carpathian tributaries to the Vistula have been analysed to select reaches satisfying two conditions: (1) they experienced considerable channel downcutting in the last decades, the period for which reliable discharge data exist; and (2) they are long enough to allow significant flood wave transformation, but the increase in basin area and thus in volume of flood waves on their length is relatively low.

A few reaches of the Skawa, Wisłoka and Wisłok Rivers have been chosen, and they consistently reveal a marked coincidence of channel downcutting and magnification of peak discharges at a lower station. This shows the importance of channel incision in flood-flow modification under conditions of a fixed river sinuosity. In fact, by the trial and error method, a correcting factor may be found which causes the cumulative curve of a corrected annual maxima-ratio to almost mimic the curve showing changes in vertical channel position (Figure 5). When lower or higher values of the correcting factor are used, the similarity of the curves vanishes.

The empirical way of searching for the best correcting factor indicates that the consistence of the growth in volume of flood waves in the Gdów–Proszówki reach and of the correcting factor in the Raba River was accidental, and raises the question of the significance of the latter. It is evident from Figure 5 that the factor differs from an average ratio of annual maxima for the period, and that values of the factor may be lower than one for reaches where a strong natural tendency to flood-wave flattening must have formerly existed. It seems that the value of a correcting factor describes an average change in mean annual flood that typified any reach at the time immediately preceding the analysed period. Thus introducing the factor into the analysis shows how the conditions of peak-flow transformation have changed since the beginning of the study period.

Now an additional piece of information can be drawn from Figure 1 – at the end of the 1910s maximum annual discharges must have typically increased by about 45 per cent in the Gdów–Proszówki reach. As the

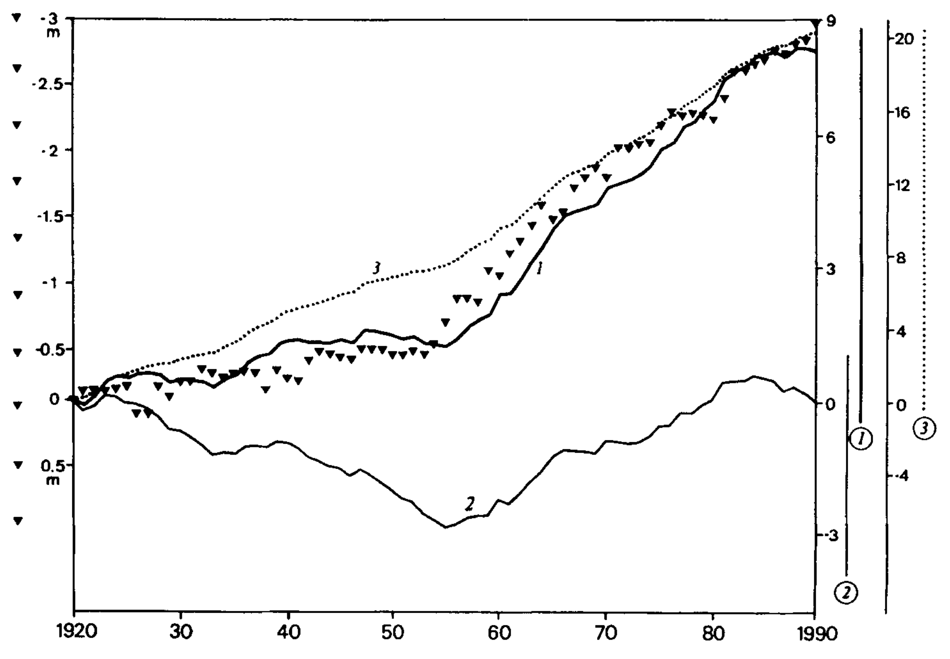

Figure 5. Channel and flood-flow changes in the Łabuzie–Brzeźnica reach of the Wisłoka River since 1920. (▼) Changes in vertical channel location in the reach as shown by the mean of changes in minimum annual water stages in the Łabuzie and Brzeźnica stations. Lines represent cumulative curves of the 'corrected' ratio of maximum annual discharge at both stations obtained for the correcting factor of the best fit ($B_{Qmax}/Ł_{Qmax}$ – 0·93, curve 1) and for the higher $B_{Qmax}/Ł_{Qmax}$ – 1·05, curve 2) or lower ($B_{Qmax}/Ł_{Qmax}$ – 0·78, curve 3) values of the correcting factor. The significance of the correcting factor of the best fit is explained in the text; the value of 1·05 is the average of the ratio $B_{Qmax}/Ł_{Qmax}$ for the study period, and thus curve 2 shows time intervals with annual maxima-ratio lower or higher than the average

Table IV. Changes in stage and some other parameters of flow at a given flood discharge which followed the channel-bed degradation at the Gdów station

	1928	1962	1972	1987
Lowest annual stage (m asl)	218·51	217·50	217·19	215·93
Flood discharge ($m^3 s^{-1}$)	160	165	166	165
Flood stage (m asl)	219·75	219·50	218·91	218·39
Mean depth at the flood flow (m)	1·22	1·54	1·89	1·75
Width at the flood flow (m)	105·5	102	74·2	63·8
Cross-sectional area of the flood flow (m^2)	129	157	140	112
Mean velocity of the flood flow ($m^3 s^{-1}$)	1·24	1·05	1·18	1·47

average increases in peak discharges and in volume of flood flows were then approximately the same, flood waves must have retained their shape along the reach – the situation characteristic of a high-flow system.

REASONS FOR THE GROWING SHARPNESS OF FLOOD WAVES IN THE REGULATED CHANNEL (1950s–1970s)

The changes in river length (shortening by 7 per cent) caused by the second phase of channelization were of less importance than changes in channel width (narrowing by 60 per cent), and, indeed, no significant shortening of the time of travel of flood waves in the Raba River has been recorded through the present century (Punzet, 1979). It shows the gradient steepening to have had little direct effect, through faster wave movement and resulting decreased attenuation, upon the observed tendency through time to increasingly magnify flood waves passing the regulated channel. Instead, the explanation seems to be

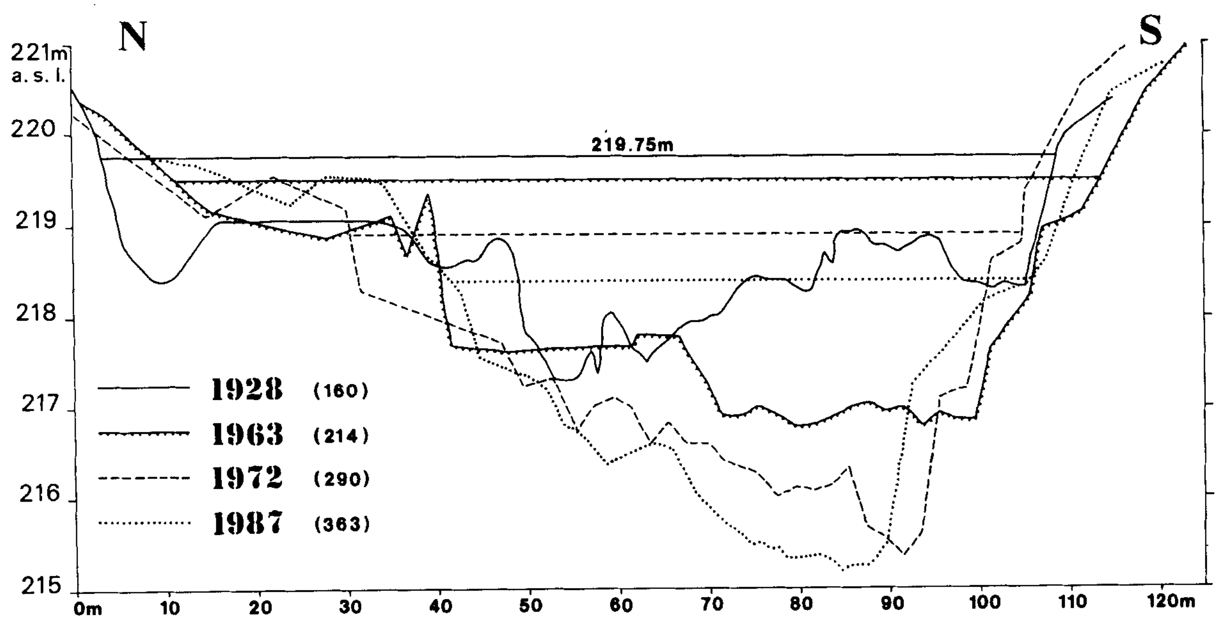

Figure 6. Changes in channel cross-section of the Raba River at the Gdów water-gauge station and associated changes in stage of a given flood discharge between 1928 and 1987. The 1962 flood flow, analysed in detail in Table IV, is shown in the background of the 1963 channel morphology. Values in parentheses are the discharge values that were (would be) attained in the particular years at the stage 219·75 m asl

related to changes in cross-section of flood flows following the channelization. It is evident that flood waves with increasingly high inflow peaks could have been sharpened, and waves of the same inflow peak were increasingly magnified as channel incision progressed in the Gdów–Proszówki reach (Table II).

With free channel development, a river reacts to diminishing sediment load through an increase in sinuosity and a change in channel cross-section (Schumm, 1968); however, no significant alteration in channel capacity is involved. Just such a tendency was realized in the Raba in around 1950 (Wyżga, 1993a), and the changes led to the reduction in flow velocity (Table IV, the period 1928–1962) compensating for the decreased sediment load. The following channelization increased flow velocity (Table IV, the period 1962–1987), and with increased transporting ability, the river lost its potential for sediment storage (Wyżga, 1993b). As a result, increasingly high discharges were associated with a given stage or, in turn, the same discharge was attained at progressively lower stage with the progress of incision (Table IV, Figure 6). The progressive reduction in width and growth in mean depth of a given flow occurred (Table IV), and increasingly high proportions of any overbank flow were concentrated in the channel zone (Figure 6).

It is suggested that the changes in transformation of flood waves leading to their increasingly peaked nature were the combined effect of the decrease in floodplain water storage due to channelization (cf. Brookes, 1987) and self-acceleration of flows concentrated in the deepened channel. The former factor alone does not explain why in-bank flows were increasingly magnified as channel incision progressed. Flows transferred in a deep, narrow and straight 'unnatural' channel are characterized by high relative smoothness (ratio of water depth to the height of protrusion of bed-material particles to the flow). It increases rapidly with growing discharge, but the associated relative decrease in resistance to flow is not moderated in a channelization-formed system by high channel-form resistance typical of natural river systems. This results in faster movement of the later, more voluminous parts of a flood wave that override its earlier parts (cf. Leopold and Miller, 1956) to cause downstream magnification of peak discharges.

DIFFERENCES IN TRANSFORMATION OF FLOOD WAVES BETWEEN VARIOUS TYPES OF RIVER SYSTEMS

The mode of transformation of flood waves is determined by the type of river system (Burkham, 1976). Developing Burkham's ideas, I propose a model that attempts to explain how various types of river systems affect flood flows, and why the channelization-formed system operates differently from low-flow and high-flow systems (Figure 7). In rivers of the temperate zone, for which water infiltration in alluvia plays a minor role, the effect of a river system upon the mode of flood-wave transformation seems to be related to changes in the pattern of flow resistance with altering discharge.

For in-bank flows the governing factor seems to be an increase in mean depth of flow with growing discharge. As mean depth grows, the influence exerted on the flow by roughness elements (grains and bed forms) diminishes, and the resulting relative decrease in boundary resistance to flow allows the more voluminous part of a flood wave to move faster from the preceding, shallower water mass. It results in overtaking and translatory overlapping of the parts of a flood wave leading to magnification of a peak flow. The higher the in-bank flow the greater the change in flow depth, and thus there is a greater increase in relative smoothness of flow on the rise of a flood, allowing greater peak-discharge magnification.

In channels of natural systems, channel-form resistance to flow must be higher than in a straight, flat-bottomed, smooth-sloped 'unnatural' channel. This high channel-form resistance inhibits the fast reduction in total resistance to flow with growing discharge. Therefore, magnification of in-bank flows in a channelized river may be greater than in channels of natural systems. Furthermore, the more deeply incised and narrower the channelization-formed channel, the faster is the increase in relative smoothness of a flow with growing discharge, and this strengthens the tendency to magnify the flood waves in their downstream movement as incision advances.

Flow resistance in an extra-channel zone is, as a rule, significantly higher than in a channel (Ven Te Chow, 1959). It causes great differences in flow velocity between an extra-channel zone and a channel that result in prolongation of a flood wave and attenuation of its peak discharge (Burkham, 1976; Archer 1989). However,

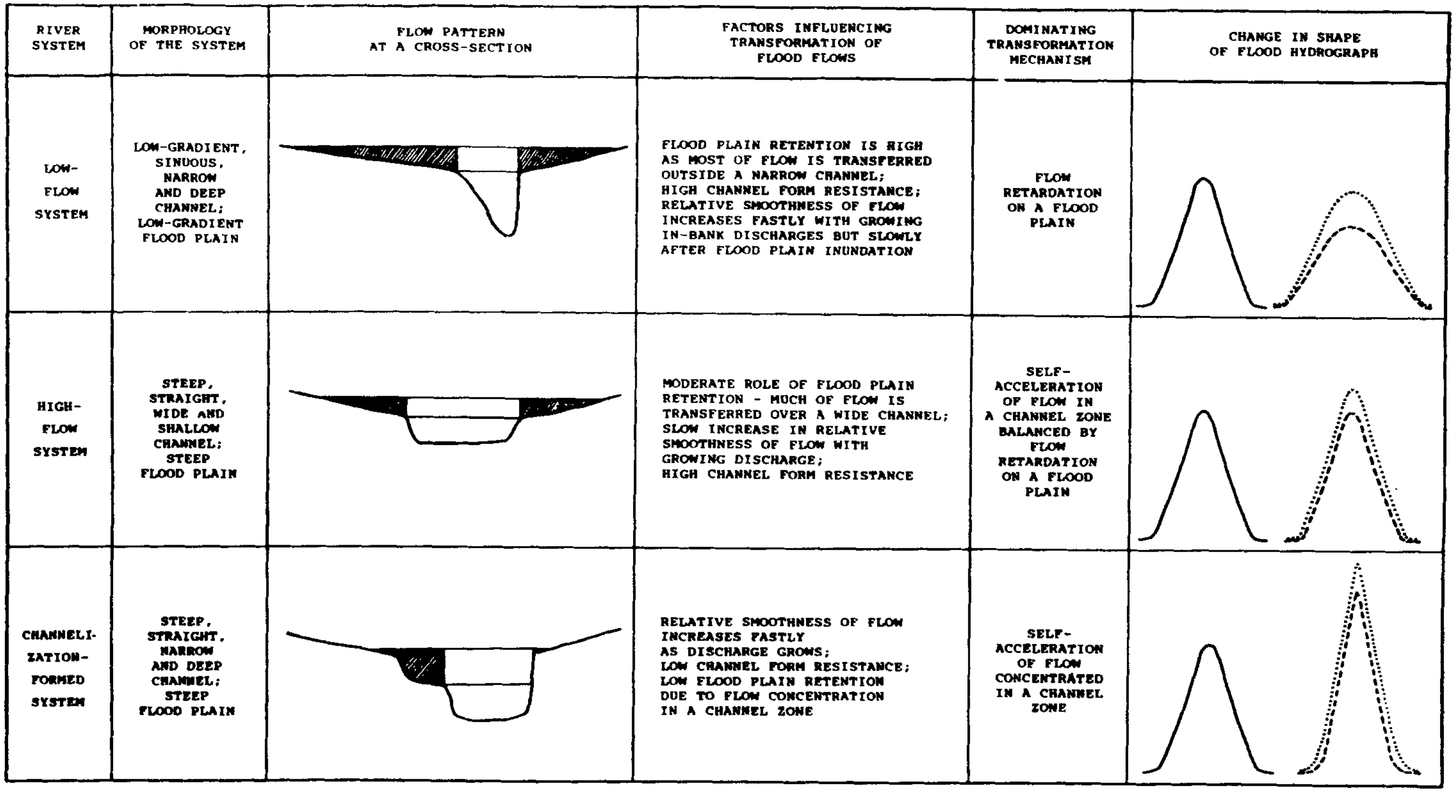

Figure 7. Conceptual model showing how morphological conditions of various river systems affect flood flows in their downstream movement. Shaded areas are parts of a given overbank flow being transferred in an extra-channel zone. Inflow hydrographs are shown by a solid line; outflow hydrographs reflecting only the action of transformation mechanisms (no water addition in a reach) are depicted by a dashed line, and those resulting from the combined action of transformation mechanisms and inflow from tributaries by a dotted line

the degree of floodplain inundation at a given discharge differs significantly between various river systems (Figure 7), and it seems to be crucial for the dissimilarities in transformation of overbank flows in various river systems.

In a low-flow system a relatively large part of the total flow is transferred in the extra-channel zone. In a channelization-formed system flow concentrates in the channel zone (in and over the deepened channel), and the amount of water flowing outside the channel is relatively low. The difference results not only from the larger capacity of the deepened channel but also from the steepened gradient of a channelized river. The latter causes an increase in velocity of a flow compensated by its reduced cross-sectional area (Table IV). A high-flow system is situated between the two extremes.

The two main factors determine transformation of overbank flows. The first is differences in flow resistance along a flood wave which cause faster movement of more voluminous, deeper flows, and tend to shorten a wave and to increase its peak discharge. The second is differences in flow resistance, and thus in flow velocity between an extra-channel zone and a channel, which tend to prolong and flatten a wave. The first factor is most active in a channelization-formed system because of the greater rate of increase in mean depth of flow (and in relative smoothness of flow) with growing discharge. On the other hand, the second factor is most significant in a low-flow system as most of the flow is transferred outside a narrow channel.

In the temperate zone inflow from tributaries considerably enlarges the volume of a flood wave on its way down the main river, whereas in the arid and semiarid zones flood waves may pass long distances without significant water addition. Therefore, the effect of the described transformation mechanisms upon the change in shape of flood waves should differ depending on whether or not water addition from tributaries takes place in a reach (Figure 7; see also Burkham, 1976).

Flood waves may be markedly flattened when passing a low-flow system without appreciable water addition. With the addition of water the ability of the system to reduce peak discharges is lowered; however, the system tends to inhibit the growth in flood magnitude despite significantly increased flood volumes. Flood waves passing a high-flow system in the semiarid zone were observed to retain their shape and magnitude (Burkham, 1976) but their peak discharges should be somewhat increased if inflow from tributaries occurs. Finally, an 'unnatural', channelization-formed system increases the sharpness of flood waves, and inflow from tributaries contributes to an additional increase in peak discharges.

CONCLUDING REMARKS

1. Two distinct stages may be distinguished in the geomorphic evolution of the Raba River since the 1920s, and they are clearly reflected in the pattern of changes in flood flows passing the stream system. With stable vertical channel position, the river increased its sinuosity during the 1920s to 1940s, and the change was accompanied by the growing ability of the system to attenuate flood waves. As a result, in the 1940s inflow and outflow peak discharges were very similar despite a significant increase in flood volume in the study reach. The temporal change in flood-flow transformation may be related to the increasing role of floodplain water storage as the river evolved into a flow-flow system (cf. Burkham, 1976).

Subsequently, streambed degradation has been induced due to channelization works which straightened and narrowed the river. As channel incision progressed, peak flows of flood waves were increasingly magnified in the reach. The increasingly peaked nature of flood waves was compensated by their shortened time-bases. It was the increasing concentration of flood flows in a channel zone with the advancing incision, that reduced floodplain retention and caused self-acceleration of flows in a deepened channel. The change in shape of flood waves passing the deepened reach was greatest for bankfull flows, as indicated by the highest magnification of peak discharges, and diminished for lower in-bank flows and higher overbank flows.

2. During the present century a marked increase in the occurrence of extremely high stages, and thus in flood frequency, has been observed within the upper Vistula River drainage basin (Punzet, 1973, 1981). To explain the growing probability of flood occurrence on Carpathian tributaries to the Vistula, a diminishing retention potential of the basins due to human activity and channel regulation was invoked (Punzet, 1981; Klimek, 1987); however, there have been no means to decide about the role played by each of the factors.

The method introduced in this paper allows, by comparing inflow and outflow peak discharges, to separate

changes in flood flows accomplished in a reach under investigation from those born in the upstream part of the catchment, and, by introducing a 'correcting factor', to see how the modifying influence exerted on flood flows by the reach (due to transformation of flood waves and increasing their volume) changed during the study period. Finally, relating temporal variations in the 'corrected' ratio of outflow/inflow peak discharges to changes in vertical channel location makes it possible to estimate the significance of alterations in a channel itself for observed trends of flood magnitude.

In fact, the 20th century downcutting of Carpathian tributaries to the Vistula, induced by channelization (Wyżga, 1991, 1993b), must have been a very important reason for the increasing flood hazard. This is testified by the high consistency of variations of the 'corrected' peak-discharge ratio and of changes in vertical channel location observed in the analysed rivers (Figures 1, 5).

3. Both gradient oversteepening and channel narrowing, caused by channelization, lead to formation of a river system being characterized by a steep, straight, narrow and deep channel. Such morphological features distinguish the system from natural low-flow and high-flow systems. In fact, the former may be maintained merely in the presence of regulation structures.

Being distinct morphologically, the channelization-formed system is also characterized by specific mechanisms of flood-flow transformation. Concentration of flow in a channel zone considerably reduces floodplain water storage. It also causes a rapid increase in relative smoothness of flow with growing discharge, and this allows self-acceleration of flow in a deepened channel. As a result, when passing an incised reach flood waves are progressively concentrated, thus raising peak discharge and shortening flood duration.

4. A reduction of flood hazard was one of the main aims of the channelization of Carpathian rivers; however, it had an adverse effect. In fact, the danger has been merely shifted downstream, and at the same time magnified there owing to the increasingly peaked nature of flood waves passing the channelized reaches and to the channel aggradation that takes place downstream of degraded reaches. In the light of the presented results the question arises as to whether the method of reducing flood hazard in southern Poland by means of channelization of Carpathian rivers is really profitable. Thereby, floodplain areas in the valleys of Carpathian rivers, where soils are poor and crops low (because of the soils and severe climate), are protected from flood damage. But it causes the growing flashiness of flood waves in the Vistula River valley and in the lowest reaches of its tributaries where intensive agriculture, industry and towns are threatened.

If an alternative policy were realized, allowing the main Carpathian rivers to develop their channels freely when meandering on the floodplains could result, under the present regime conditions, in the formation of narrow, deep and sinuous channels as well as in the re-establishment of the conditions of floodplain storage and peak-discharge attenuation. But the cost of such a choice would be the loss of channel stabilization within the valley floors.

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